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Optimization of Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) Systems

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Abstract

The increasing demand for high performance systems has triggered the emergence of optimal control problems which have become a hot topic recently. Related to the concept of how the condition of an optimal control system is the concept of optimizing a control system which shows a balance in the form of a meeting point between selecting a performance index and engineering with the aim of creating an optimal control system within the limits of physical constraints. In creating these conditions, it is necessary to have control system decision rules that can reduce the savings value from ideal behavior. In compiling this report, the author will explain the application of the LQR and LQT DC Motor Plant processes which are equipped with a datasheet. The use of MATLAB is also needed in the preparation of this report to include datasheets in the MATLAB script which will then be simulated with MATLAB Simulink. The purpose of this process is to see how the step response is generated. Meanwhile, the type of DC motor used is type C24-L50, equipped with values for moment of inertia, damping ratio, inductance, resistance, and motor constants. in carrying out the experiment there is no series that is designed to reach the desired set point of the scope graph, because the application of a mathematical model from an existing data sheet does not use damping so that the graph cannot reach the set point.

Keywords: system optimization, DC C42-L50, LQR, LQT

1. Introduction

The increasing demand for high-performance systems has driven the emergence of optimal control problems, which have recently become a significant topic of interest. The concept of an optimal control system revolves around the balance between selecting performance indices and designing engineering strategies to create optimal systems within physical constraints. To achieve this, it is necessary to implement control decision rules that minimize deviations from ideal behavior (Ogata, 2010; Nise, 2015; Dorf & Bishop, 2017).

The primary focus of this report is to discuss the Linear Quadratic Regulator (LQR) method, which serves as an optimal control approach in state-space systems. The LQR controller operates with two key parameters: the Q and R matrices. Specific adjustments to these parameters are required to optimize the control function to meet system needs. Applications of the LQR method include speed control of induction motors, generator frequency regulation, and quadcopter drones (Lewis et al., 2012; Nugraha et al., 2023a; Franklin et al., 2019).

The connection between system optimization and the LQR method lies in how LQR, when combined with system optimization techniques, results in tools with enhanced performance and reduced errors. For instance, the Linear Quadratic Integral Tracking (LQIT) method is an extension of LQR that incorporates an integral controller to eliminate steady-state errors during tracking. Simulated results indicate that LQIT can achieve minimal steady-state error within a 3% criterion, effectively returning suspension systems to their set positions despite disturbances (Anderson & Moore, 2007; Doyle et al., 1992; Kwakernaak & Sivan, 1972).

In this report, the author will elaborate on the application of LQR and Linear Quadratic Tracking (LQT) methods to a DC motor plant, supported by its datasheet. MATLAB is employed to input the motor's datasheet into MATLAB scripts, followed by simulations using MATLAB Simulink. This process aims to analyze the step response of the system and evaluate its performance under varying conditions (Nugraha et al., 2024a; Ziemer et al., 1998; Bryson, 2018).

The DC motor used in this study is the C24-L50 model, featuring specified values for moment of inertia, damping ratio, inductance, resistance, and motor constant. This motor type is well-suited for testing the LQR and LQT methods to evaluate their performance in controlling DC motor dynamics. The simulations help demonstrate the effectiveness of these control methods in optimizing system performance while reducing errors and disturbances (Hughes, 2005; Chen & Khalil, 2002; Astrom & Murray, 2008).

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2. Material and methods

2.1. research stages

1. Literature Review
   The search for references is conducted to facilitate the author in composing the paper. References serve as a literature review and help the author gain a deeper understanding of the problem to be discussed in the paper. Additionally, references act as a guideline in the paper's development. The references are sourced from various materials, including articles, journals, datasheets, and others.
2. Mathematical Model Development
   In this stage, the author performs mathematical calculations to theoretically validate the findings from the literature review. This phase results in a mathematical model that will later be implemented in the designed system.
3. Circuit Design
   The circuit design is developed using MATLAB software. Several types of circuits are created, including LQR, LQT, LQR with noise, and LQT with noise.
4. Results and Discussion
   This section presents the results of the designed circuits using MATLAB. It includes circuit diagrams and waveform outputs generated by the oscilloscope. A comparison table is also provided to evaluate the results of LQR, LQT, LQR with noise, and LQT with noise circuits.
5. Conclusion
   In this stage, the author draws conclusions based on the results and discussion. Several key points are highlighted as the main findings of the research, which serve as benchmarks for the study's outcome.

2.2. Problem Solving Methods

C42 Series Specifications

C42 SERIES SPECIFICATIONS – *Continuous Stall Torque 145 - 560 oz-in (1.024 - 3.955 Nm)*
Peak Torque 1100 - 3500 oz-in (7.768 - 24.716 Nm)

Part Number*		C42-L50			C42-L70			C42-L90		
Winding Code**		10	20	30	10	20	30	10	20	30
L = Length	inches	5.00			7.00			9.00		
	millimeters	127.0			177.8			228.6		
Peak Torque	oz-in	1100.0	1100.0	1100.0	2400.0	2400.0	2400.0	3500.0	3500.0	3500.0
	Nm	7.768	7.768	7.768	16.948	16.948	16.948	24.716	24.716	24.716
Continuous Stall Torque	oz-in	145.0	145.0	145.0	400.0	400.0	400.0	560.0	560.0	560.0
	Nm	1.024	1.024	1.024	2.825	2.825	2.825	3.955	3.955	3.955
Rated Terminal Voltage	volts DC	12 - 48	24 - 72	36 - 96	12 - 48	24 - 72	36 - 96	24 - 60	24 - 84	36 - 96
Terminal Voltage	volts DC	48	72	84	36	48	72	48	60	90
Rated Speed	RPM	3226	1885	1528	1160	1130	1060	1273	1238	1517
	rad/sec	338	197	160	121	118	111	133	130	159
Rated Torque	oz-in	80.3	98.2	126.7	248	237	263	336	341	320
	Nm	0.57	0.69	0.89	1.75	1.67	1.86	2.37	2.41	2.26
Rated Current	Amps	5.3	2.7	2.4	8	5.75	3.9	8.5	6.7	5
Rated Power	Watts	192	137	143	214	198	206	317	312	368
	Horsepower	0.26	0.18	0.19	0.29	0.27	0.28	0.42	0.42	0.48
Torque Sensitivity	oz-in/amp	20	46	65	39	52.8	85	50	64.3	82
	Nm/amp	0.1412	0.3248	0.4590	0.2754	0.3728	0.6002	0.3531	0.4541	0.5791
Back EMF	volts/KRPM	14.8	34	48	28.8	39	62.85	37	47.5	60
	volts/rad/sec	0.1413	0.3247	0.4584	0.2750	0.3724	0.6002	0.3533	0.4536	0.5730
Terminal Resistance	ohms	0.7	4	5.7	0.62	1.2	2.6	0.6	0.95	1.45
Terminal Inductance	mH	1.3	6.8	13.8	2	3.7	9.8	2	3.3	5.4
Motor Constant	oz-in/watt^1/2	23.9	23.0	27.2	49.5	48.2	52.7	64.5	66.0	68.1
	Nm/watt	0.169	0.162	0.192	0.350	0.340	0.372	0.456	0.466	0.481
Rotor Inertia	oz-in-sec²	0.09	0.09	0.09	0.21	0.21	0.21	0.31	0.31	0.31
	g-cm²	6355.4	6355.4	6355.4	14829.2	14829.2	14829.2	21890.7	21890.7	21890.7
Friction Torque	oz-in	14.0	14.0	14.0	20.0	20.0	20.0	24	24	24
	Nm	0.10	0.10	0.10	0.14	0.14	0.14	0.17	0.17	0.17
Thermal Resistance	°C/watt	2.20	2.20	2.20	1.30	1.30	1.30	0.85	0.85	0.85
Damping Factor	oz-in/KRPM	5.25	5.25	5.25	10.00	10.00	10.00	10.00	10.00	10.00
	Nm/KRPM	0.037	0.037	0.037	0.071	0.071	0.071	0.071	0.071	0.071
Weight	oz	110	110	110	208	208	208	262	262	262
	g	3118	3118	3118	5870	5870	5870	7428	7428	7428
Electrical Time Constant	millisecond	1.8571	1.6500	2.3684	3.2258	3.0833	3.6923	3.3333	3.4737	3.7241
Mech. Time Constant	millisecond	22.28412	24.09874	17.2181	12.1367	12.81294	10.79077	10.52659	10.39549	9.565579
Speed/Torque Gradient	rpm/oz-in	-2.36486	-2.55754	-1.82802	-0.55189	-0.58275	-0.48869	-0.32432	-0.31104	-0.29472

Notes:
1. For MS (military style) connector, please specify connector housing and terminal.
2. Data for informational purposes only. Should not be considered a binding performance agreement. For specific applications, please contact the factory.

*Many other custom mechanical options are available – consult factory.
**Many other winding options are available – consult factory.

figure 1. data sheet Motor DC

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a. Order 1 and Order 2 calculations
1st Order Modeling

General form of 1st order transfer function

$$G(s) = \frac{K}{\tau s + 1}$$

1st order DC motor
Based on the DC motor datasheet, the 1st order equation is obtained:
Where \tau\ =\ K.i so that

$$K = \frac{\tau}{i} = \frac{0,32}{5,3} = 0,06$$

DC motor 1st order equation:

$$G(s) = \frac{0,06}{0,32s + 0,06}$$

b. Matlab Script Program
LQR

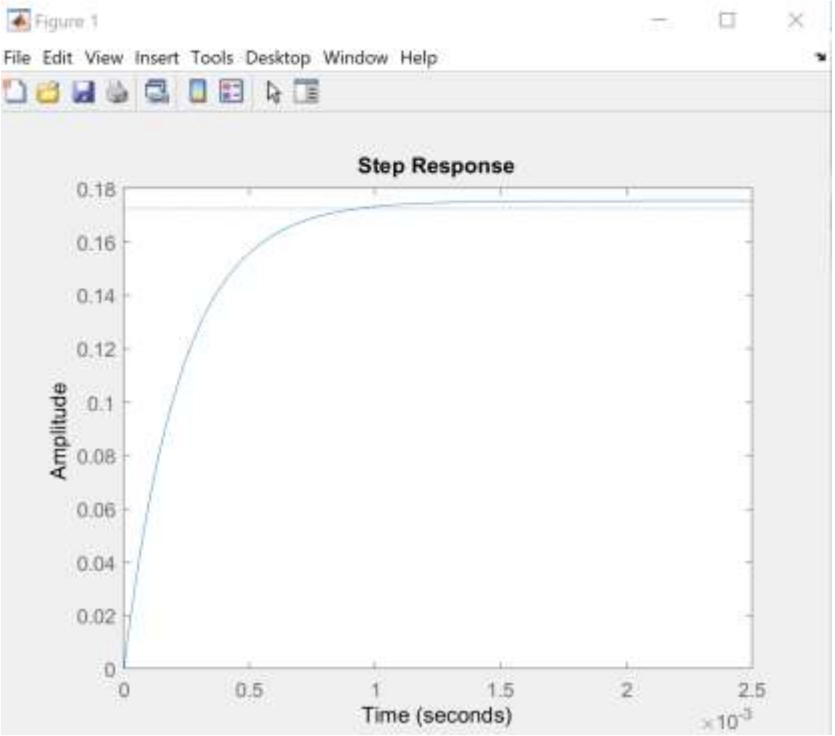

Figure 2 result in matlab

```
close all; clc; clear;
%LQR
J = 0.09
b = 0.037
K = 0.06
R = 5.7
L = 0.0013
%state space
A = [-R/L -K/L; K/J -b/J]
B = [1/L; 0]
```

C = [1 0]
D = 0
Q = [0.00000001 0; 0 0.000000001];
R = 1;
[K,S,e] = lqr(A,B,Q,R);
Ac = A - B*K;
step (Ac,B,C,D,1)

LQT

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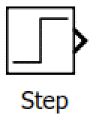
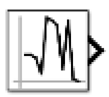
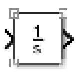
daus lqt.m

```
%Parameter Sistem MSD
m=2; %massa
k=8; %Spring
b=6; %Damp
%Matrix Pada state
A=[0 1;-k/m -b/m];
B=[0;1/m];
C=[1 0];
%Bobot
Q=[1 0;0 1];
R=10;
[S,eig,G] = care(A,B,Q) %Riccati 0=A'S+SA-SB(inv R)B'S+Q
Kx=inv(R)*B'*S %Fbck Gain Kx
Kr=(Kx*(inv(A))*B-eye(1))*(inv(C*(inv(A))*B))
Ahat=[0 1 0;-k/m -b/m 0;1 0 0]
Bhat=[0;1/m;0]
%Bobot hat
Qhat=[1 0 0;0 1 0;0 0 1];
Rhat=6;
[Shat,eighat,Ghat] = care(Ahat,Bhat,Qhat) %Riccati 0=A'S+SA-SB(inv R)B'S+Q
Khat=inv(Rhat)*Bhat'*Shat
Kw=Khat(:,3)
```

c. **Tools Simulink**

Komponen	Nama Komponen
	Step
	andom Number
	Gain
	Sum
	Integrator

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	Scope

Table 1. tools Simulink in matlab

3. Results and discussion

3.1. LQR

The Linear Quadratic Regulator (LQR) is a control method applied to systems based on state-space representation. This method is widely used in control engineering due to its ability to optimize system performance while maintaining stability (Faj'riyah et al., 2021). LQR works by determining an optimal control input to minimize a given performance index, ensuring that the system operates efficiently (Nugraha et al., 2024b).

The controller in LQR relies on two key weighting matrices, Q and R, which must be carefully selected to achieve optimal control actions. The Q matrix influences the state error penalty, while the R matrix determines the control effort penalty. By adjusting these parameters, engineers can fine-tune the system's response, balancing between fast stabilization and minimal control energy usage.

One practical implementation of the LQR method is in controlling the speed of induction motors, ensuring they operate within desired performance limits. By applying LQR, motor speed can be adjusted dynamically while maintaining stability, even in the presence of load variations and disturbances. This makes it a preferred choice for high-performance motor control applications (As'ad & Nugraha, 2022; Khabibi et al., 2020).

Another common application of LQR is in frequency regulation in power generation systems. In a generator, maintaining a stable frequency is crucial for ensuring a reliable power supply. LQR helps in adjusting control parameters to counteract disturbances, thereby improving the stability of power grids and preventing fluctuations that could affect electrical equipment.

Additionally, LQR plays a significant role in the control of quadcopter drones, where precise stabilization is required. The method helps maintain balance and trajectory even when external disturbances such as wind or sudden movements occur. By keeping the system at the desired setpoint, LQR ensures that drones can operate smoothly and reliably under various conditions.

a. LQR

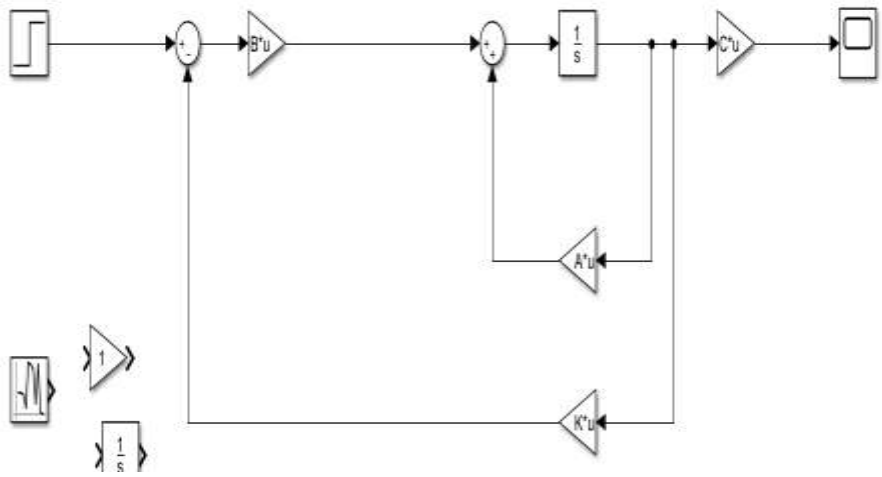

Figure 3. wiring LQR in matlab

b. Simulation result

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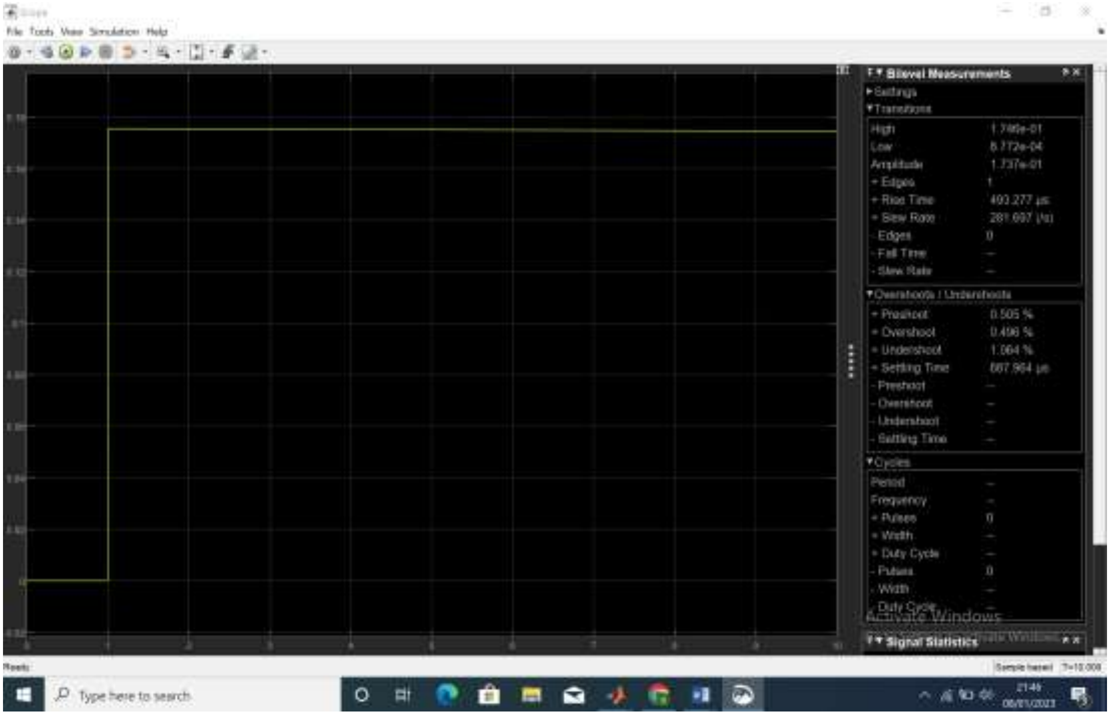

Figure 4. simulation result

3.2 LQT

The Linear Quadratic Regulator (LQR) is an optimal control method designed for linear systems using a quadratic performance criterion to solve regulation problems. It is widely used in control engineering to maintain system stability while minimizing energy consumption. By applying LQR, a system can be controlled effectively to reach the desired state with minimal deviation.
LQR works by determining an optimal control law based on the system’s state-space representation. It uses a quadratic cost function that penalizes deviations from the desired state and excessive control effort. The balance between these penalties is adjusted using the weighting matrices Q and R, which influence the system's performance and stability.

On the other hand, Linear Quadratic Tracking (LQT) is an extension of LQR that focuses on tracking a reference trajectory rather than simply stabilizing the system at a fixed state. This method ensures that the system follows a desired path over time while minimizing tracking errors and control effort. It is particularly useful in applications where precise motion control is required.
The main difference between LQR and LQT lies in their objectives. While LQR aims to bring the system to a steady-state point efficiently, LQT ensures that the system follows a predefined trajectory. This makes LQT ideal for dynamic systems such as robotic arms, autonomous vehicles, and flight control systems, where continuous movement tracking is necessary.

Both LQR and LQT play a crucial role in modern control engineering by improving the performance and efficiency of linear systems. By carefully selecting the Q and R parameters, engineers can fine-tune the system response to achieve optimal control. These methods help maintain stability, reduce energy consumption, and enhance overall system performance, making them essential in various industries.

a. LQT

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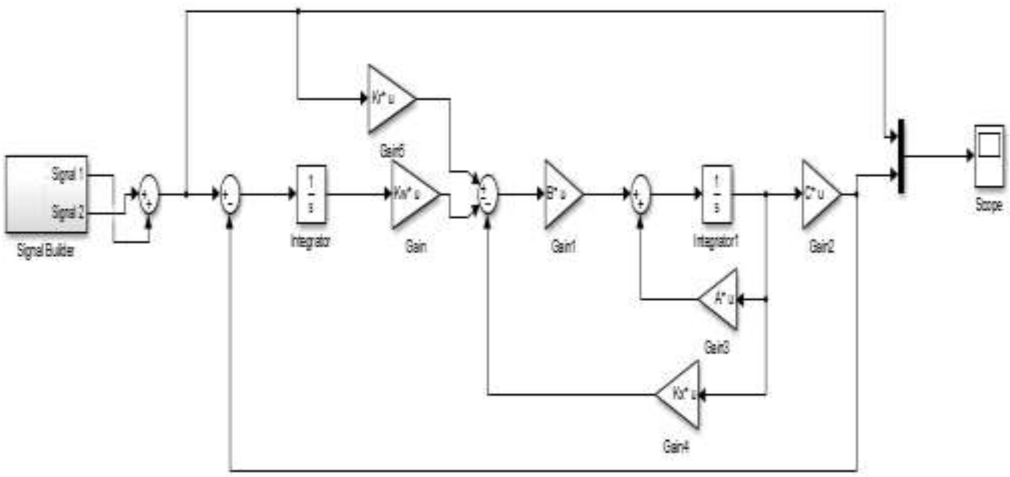

Figure 5. wiring LQT

b. Simulation result

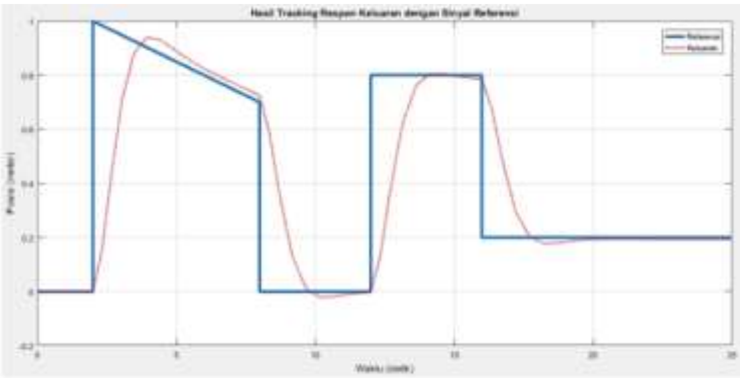

Figure 6. semulation result LQT

3.3 discustion

a) Step Response Analysis of the LQR DC Motor C42-L50 Without Noise
According to Table 2, the step response graph of the Linear Quadratic Regulator (LQR) applied to the DC motor C42-L50 demonstrates the behavior of the system without the influence of noise. The results indicate that the step response output reaches an amplitude of 0.17, which falls short of achieving the predefined setpoint. The motor exhibits a rise time of approximately 4.932 seconds, which is considered optimal for this system. However, the motor's performance reveals an overshoot of 0.496%, reflecting a minor deviation beyond the desired output, and a relatively significant undershoot of 1.064%, representing a noticeable drop below the intended steady-state value. This indicates that while the system achieves moderate response times, further optimization might be necessary to improve its ability to closely match the desired output, particularly in scenarios with high-performance requirements.

b) Performance Evaluation of LQIT Controller Under Variable Disturbances
The controller's performance was evaluated under varying conditions, simulating real-world disturbances such as shocks or vibrations affecting the system's suspension. The simulation results, represented graphically, show a blue line indicating the reference signal, while the red line represents the system's response when the Linear Quadratic Integral Tracking (LQIT) controller is applied. The findings reveal that the system equipped with the LQIT controller effectively tracks the reference trajectory, ensuring alignment with the desired setpoint despite external disruptions.

During the transient response phase, the system achieves a steady-state error of approximately 3%, which is well within acceptable limits. This steady-state error demonstrates the controller's ability to maintain accurate tracking even in the presence of disturbances. The consistent average steady-state error of 3% signifies that the LQIT controller effectively compensates for positional changes caused by shocks or vibrations. As a result, the system is able to return to the specified reference point promptly and accurately, ensuring that disturbances affecting the suspension are efficiently mitigated.

Furthermore, the controller's ability to regulate the system during transient conditions showcases its robustness and adaptability. In practical applications, such as vehicle suspension systems, where dynamic disturbances are frequent, the LQIT controller ensures that positional tracking is maintained with minimal error. This capability enhances the overall stability and performance of the suspension system, providing a smoother and more reliable response under fluctuating operational conditions.

Overall, the analysis highlights the advantages of using both LQR and LQIT methodologies in dynamic control systems. The combination of optimal control theory and tracking precision ensures not only stability and responsiveness but also the capacity to handle external disturbances effectively. These qualities make LQIT a preferred choice for advanced control systems requiring high precision and reliability.

4. Conclusion

The optimal control technique discussed in this paper utilizes the Linear Quadratic Regulator (LQR) approach. In this method, the Q matrix elements are determined by multiplying the transpose of the system's C matrix by the system's C matrix itself. This approach ensures that the weight matrix Q accurately reflects the system's state dynamics, optimizing its control performance. Meanwhile, the R matrix elements are fine-tuned through experimental tuning, where an optimal value of 0.000001 is applied. This selection of R is crucial, as it influences the trade-off between control effort and system response, ensuring a balance between stability and performance.

The application of the LQR control system was tested, and the results indicate that it significantly improves the system's time constant (τ). When compared to a conventional Proportional-Integral-Derivative (PID) controller, the LQR approach demonstrated a more optimal response time, reducing the time constant by approximately 0.02 seconds. This reduction highlights the effectiveness of LQR in achieving faster system stabilization, which is particularly beneficial in real-time control applications where rapid response is necessary.

Further simulation tests were conducted to evaluate the performance of the Linear Quadratic Integral Tracking (LQIT) controller in a simplified suspension system model. The system consists of three key mechanical components: mass (M), spring (K), and damper (D). The LQIT controller was designed to handle external disturbances effectively by adjusting its control actions based on real-time deviations from the reference trajectory. The results demonstrated that LQIT successfully mitigates shocks and vibrations, ensuring that the system's motion remains smooth and well-regulated.

One of the key performance indicators in this study was the steady-state error, which measures how accurately the system tracks its reference trajectory. The simulation results showed that the LQIT controller achieved an average steady-state error of only 3%. This level of precision indicates that the controller is capable of maintaining high tracking accuracy, even when the system is exposed to unexpected disturbances. The ability to maintain such a low steady-state error ensures enhanced performance, particularly in applications where precise positioning and stability are critical, such as in automotive suspension systems and robotics.

In conclusion, the LQR and LQIT control techniques have been shown to offer significant improvements in system response and disturbance rejection. The LQR method provides a more optimized time constant compared to traditional PID control, while the LQIT controller enhances tracking accuracy and disturbance rejection capabilities in dynamic systems. These findings suggest that optimal control strategies such as LQR and LQIT can be highly effective in improving the performance of mechanical and electrical systems, making them valuable approaches for future advancements in control engineering.

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